NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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No. 1037

A STUDY OF COMBUSTION IN A FLOWING GAS

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SUMMARY

The results of a preliminary study of combustion in flowing gases are given and apparatus for obtaining high rates of heat release per unit volume of combustion space is described. The principal feature of the combustion apparatus is an electrical element (Globar) mounted concentrically within a stainless-steel pipe. The annular space between the inner and outer elements serves as the combustion space.

Tests were made over a wide range of fuel-air ratios, inlet-mixture velocities, and electrical heat inputs, using propane gas as the fuel. The effect of these variables on the extent of combustion and mixture inflammability was investigated.

The results obtained with the combustion tube are as follows:

1. The greater the surface-volume ratio, or the greater the amount of heat addible to the gas stream, the greater the inlet-mixture velocity at which appreciable combustion can be obtained.

2. For a given fuel-air ratio, the total rate of heat output (Btu/sec), equal to the sum of the electrical and chemical energy released, increases with increasing velocity. However, both the extent of combustion, as measured by the combustion factor α, and the total heat output (Btu/lb of fuel) decrease with increase of velocity for most of the fuel-air ratios tested.

3. The most inflammable mixtures, as determined by the length of heating element necessary to produce ignition, are those of approximately stoichiometric proportions of fuel and air.

INTRODUCTION

An investigation of some of the basic factors affecting combustion in a flowing gas stream was instituted in order to supply a basis for future design and evaluation of jet-propulsion power plants. The tests were made using a combustion tube that incorporated an annular heating space in which a fuel-air mixture was burned and the resulting energy release measured. This type of apparatus was selected primarily because of its suitability and convenience for the study of individual factors affecting combustion and is not meant to be a suggested type of jet-propulsion burner or its prototype.

The data reported were obtained as part of a survey performed at the Cleveland laboratory of the NACA early in 1944 covering a range of operating variables including inlet-mixture velocities, heat additions, and fuel-air ratios. The purpose of the survey was to obtain qualitative knowledge of the effects of these variables on combustion phenomena, as well as to discover the capabilities of the apparatus.

APPARATUS

The combustion tube and the flow diagram are shown in figures 1 to 3. The combustion tube consists of a horizontal silicon-carbide electric heating element (Globar) placed concentrically within a stainless-steel pipe, thus forming a narrow annular space whose width is 0.06 and 0.12 inch, respectively, for the 5/8- and 1/2-inch-diameter heating elements used. Through this space, a metered fuel-air mixture is passed. Because of the high rate of heat transfer obtained in such a small annulus, the mixture is rapidly heated from room temperature to its ignition temperature, which causes combustion to take place in a confined, relatively short space of 15 inches or less. The completeness of combustion can then be calculated from a heat balance for the combustion tube.

The air for the tests was supplied from a laboratory system under a pressure of 100 pounds per square inch. The fuel was a commercial product containing a minimum of 99 percent propane. The air and fuel flows were controlled by pressure-regulating valves and measured by orifices. Electrical power was supplied by a 14 kilovolt-ampere saturable reactor-voltage regulator.

In order to make a heat balance for the combustion tube, as well as to obtain information pertinent to the combustion process, the following measurements were made:

(1) Air and fuel flows

(2) Inlet and exhaust temperatures

(3) Tube and heating-element surface temperatures

(4) Electrical power input to the heating element

(5) Pressure drop across the combustion tube

The maximum error of the individual measurements used for the calculation of the heat balance was estimated to be less than ±10 percent. Because estimations of the specific heat of the exhaust gases and an approximation of the heat losses through conduction, convection, and radiation introduced a considerable error, the uncertainty of any results shown in the present paper may be as high as ± 25 percent.

SYMBOLS

α combustion factor, dimensionless

c_p mean specific heat at constant pressure, Btu per pound per $^{\circ}F$

C_1 dimensional constant

D_e hydraulic diameter $(D_2 - D_1)$, which is equal to four times the hydraulic radius, feet

D_1 diameter of Globar heater, feet

D_2 inside diameter of pipe, feet

ΔH net theoretical heat of reaction of propane, Btu per pound air

L heating length required for ignition, feet

q rate of heat energy input or output, Btu per second

Subscripts referring to q:

c energy liberated by combustion

e electrical power input

h increase of total energy in gas

l total energy loss

max theoretical maximum energy liberated by combustion

primo (') indicates air datum run

T_{av} weighted average temperature of inside surfaces, °F

T_i inlet-mixture temperature, °F

T_{ig} ignition temperature of fuel-air mixture, °F

ΔT_a increase in temperature of the air from inlet to exhaust conditions, °F

ΔT_m increase in temperature of fuel-air mixture from inlet to exhaust conditions, °F

V maximum inlet-mixture velocity for ignition, feet per second

W_a weight flow of air, pounds per second

W_m weight flow of fuel-air mixture, pounds per second

EXPERIMENTAL PROCEDURE AND CALCULATIONS

In order to determine the effect on combustion of the addition of heat from hot surfaces, the inlet-mixture velocity, and the fuel-air ratio, about 500 runs were made covering the following ranges:

Inlet-mixture velocity, feet per second	0-200
Power input, or heat addition, kilowatts	0.50-6
Fuel-air ratio	0-1.00

Illustrative data have been selected for presentation in this report. For the data presented, the absolute pressure varied between 1 and $1\frac{1}{2}$ atmospheres and the inlet-mixture temperature was 80° F. The pressure drop across the tube during combustion was generally less than 15 inches of water.

The fuel-air mixture was admitted to the tube, ignited by increasing the electrical power input, and burned. When stable conditions of combustion were obtained, pertinent pressures, temperatures, and powers were recorded. The flame-front position was estimated from the abrupt change in temperature along the outer tube surface that occurred during combustion. Physical limitations of the apparatus with regard to maximum allowable temperatures caused gaps in the data. The maximum observed Globar temperature was about 2900° F.

A combustion factor was used as a measure of the extent of combustion. The combustion factor α is defined as the ratio of the actual rate of heat liberated by combustion to the theoretical maximum rate of heat liberated by combustion based on the standard net heat of combustion of propane.

The actual rate of heat-energy liberated q was obtained by a simple heat balance for the combustion tube. The heat balance included (1) the electrical power input q_e, (2) the rate of increase in heat content of the gaseous mixture q_h, (3) the combustion-tube rates of heat loss through radiation, conduction, and convection q_l, and (4) the rate of combustion-energy release q_c.

The heat balance for a combustion run can then be expressed by

$$q_c = q_h + q_l - q_e \tag{1}$$

where q_l is obtained from the data for air-datum runs at a similar temperature level and distribution as for the combustion run.

For the air-datum runs, in which no fuel was introduced, the heat-balance equation is

$$q'_e = q'_h + q'_l \tag{2}$$

The value of q'_l is determined by the difference between the measured value of q'_e and the calculated value of q'_h, where q'_h is equal to $W_a c_p \Delta T_a$. The values of q'_l are determined for a range of conditions by making air-datum runs for a range of temperatures and temperature distributions of the combustion-tube outer surface.

For simplification of the calculation of q_h, the reaction was assumed to take place at the inlet-mixture temperature with the resulting products being heated to the final temperature (reference 1, p. 204). The rate of increase in heat content can then be calculated from

$$q_h = W_m c_p \Delta T_m \tag{3}$$

The maximum rate of energy release for complete combustion of the fuel can be expressed by the relation

$$q_{max} = \Delta H W_a \tag{4}$$

where ΔH is a function of fuel-air ratio for lean mixtures and constant for rich mixtures. The combustion factor α is then calculated from the relation

$$\alpha = \frac{q_c}{q_{max}} = \frac{q_c}{\Delta H W_a} \tag{5}$$

RESULTS

The Effect of Heat Addition on Maximum Inlet Velocity

Heat transfer from the heating element to the inlet-mixture stream rapidly raises its temperature to the ignition point, that is, to the point at which oxidation reactions will become appreciable. It is evident that the more heat which can be added to the mixture per unit time the higher the mixture velocity at which ignition and combustion will occur within a given length of chamber. An examination of figure 4 shows that the maximum permissible inlet-mixture velocity is a function of the heat addition for the two sizes of Globar heater under consideration.

The maximum permissible inlet mixture velocity may be assumed to correspond to the minimum temperature rise required for ignition to occur in a length equal to that of the combustion tube. In general, the temperature rise is a function of the mixture velocity, the power input, and the hydraulic radius of the annulus (reference 2, pp. 197-202). In this reference, the heat-transfer rate for turbulent-flow conditions in tubes and annuli is shown to increase approximately with the 0.8 power of the velocity, whereas the time of contact of the gas with the heating element is decreased in direct proportion to velocity increase. The predicted temperature rise of the stream will therefore vary inversely with the 0.2 power of the velocity. Furthermore, the heat-transfer rate varies almost inversely with the hydraulic diameter D_e. The ignition temperature for constant inlet density would then be expected to follow the equation (derived in the appendix)

$$T_{ig} - T_1 = (T_{av} - T_1)\left[1 - \exp\left(\frac{-C_1 L}{D_e^{1.2}\, V^{0.2}}\right)\right] \tag{6}$$

Equation (6) predicts, for a given ignition temperature and heated length, a greater maximum inlet velocity for a smaller hydraulic radius, or larger Globar size. The trend of the data of figure 4 agrees with this prediction. It should be noted that for a given power input the values of T_{av} will not be the same in the two annuli considered. For the larger Globar (smaller annulus) T_{av} will be smaller for two reasons: (1) for the same radiative power loss (same electrical power), the radiation per unit area of surface is smaller for the larger Globar, and (2) the convective heat transfer per unit temperature difference between gas and surface is greater at a given velocity. A given amount of electrical power is therefore dissipated from the larger Globar at a lower surface temperature. Curves of constant T_{av} superimposed on figure 4 would thus have a greater positive slope than the curves presented. The experiments were not run under conditions that isolate the ignition temperature while holding all variables but one constant. For the range of velocities and electrical power inputs in the experiments, the ignition temperatures varied between 550° to 700° F.

The Effect of Fuel-Air Ratio and Velocity on Combustion Factor and Heat Output

Figure 5, which is representative of the test data, shows the relation between fuel-air ratio, velocity, and combustion factor α. The dotted portions indicate that an abrupt decrease to zero in α occurs with decrease in fuel-air ratio at fuel-air ratios in the region of 0.02. The data in the very lean region is meager but seems characterized, as far as has been observed, by a falling off in combustion factor from a very high value to a negligible value in a narrow range of fuel-air ratios. Such an abrupt drop in α would be caused by a combustible limit but was not found in the rich range of mixture ratios tested. The value of α reaches a maximum at about 0.02 in figure 5 and decreases as the fuel-air ratio is increased; however, other data obtained in the investigation indicate that the maximum values of α occur in a region between 0.02 and 0.06. The most rapid decrease in α in the rich-mixture range occurs between fuel-air ratios of 0.10 and 0.14, after which the drop is quite gradual. For the experimental conditions investigated velocity increases produce a sensible decrease in α only in the rich region.

The effect of fuel-air ratio and velocity on the total rate of heat output is illustrated in figure 6. The total rate of heat output refers to the sum of $q_h + q_l$ or its equivalent $q_e + q_c$.

It is a useful index of the total heat generated by the unit and clearly illustrates the maximum output for fuel-air ratios near stoichiometric, the maximum being of the order of 17 Btu per second at 150 feet per second and 3.8 Btu per second electrical power input. The trend is similar for all power inputs encountered.

Figure 7 is a plot based on the total heat release per pound of fuel and reflects the marked effect of the decrease of α with increasing fuel-air ratio, as well as the effect on α of increasing the velocity. The difference in appearance between the curves of figures 6 and 7 at lean mixtures is due to decreasing fuel flow in the ordinate variable of figure 7 with decreasing fuel-air ratio.

The quantity of heat released in Btu per hour per cubic foot of combustion volume per standard atmosphere was computed from the data plotted in figures 6 and 7. The volume of the annular space with the 1/2-inch Globar is 0.0025 cubic foot. For a pressure of 1 atmosphere, the heat liberated by combustion varies between 1×10^6 and 19×10^6 Btu/(hr)(ft^3)(atm), whereas the heat release of the Globar approximates 5×10^6 Btu/(hr)(ft^3)(atm). Hence, the total rate of heat output varied from 6×10^6 to 24×10^6 Btu/(hr)(ft^3)(atm). In comparison, a conventional jet-propulsion burner releases between 2×10^6 and 6×10^6 Btu/(hr)(ft^3)(atm). The rate of combustion-energy release per unit volume for the combustion tube can thus be several times larger than for a jet-propulsion burner. It should also be noted that the heat-release values for the combustion tube were based on the total annular volume although combustion occurred in only approximately 50 percent of the total volume.

MIXTURE INFLAMMABILITY

The inflammability of a gas mixture may be described in various ways. Flame speed may be the useful criterion of inflammability if the rate at which a mixture can be burned is of interest. The relative ease with which gas mixtures can be ignited by sparks, hot spots, pilot flames, or other energy sources may also be taken as a measure of inflammability. The ignition temperature, or the temperature at which self-propagating reactions begin is another inflammability criterion. A fourth is the range of mixture proportions of fuel, oxidant, and diluent than can be ignited by a standard energy source and that are capable of self-propagation of flame.

It has been recognized in the literature that the data used as a measure of the inflammability of a gas mixture depend on the choice of the criterion of inflammability and that inflammability is a function of the intrinsic properties of the mixture and the properties of the confining system. The data of previous investigators (references 3, 4, and 5) have indicated that gas mixtures of stoichiometric proportions or with a slight excess of fuel are most inflammable with respect to the aforementioned criteria of inflammability.

In the combustion tube, mixture inflammability is associated with the flame-front position, which is the upstream boundary of the burning zone. The farther upstream in the tube the flame front will stabilize for a given inlet velocity, or the lower its ignition temperature, the more inflammable is the mixture. Relating inflammability to the flame-front position appears to be a more satisfactory procedure for the combustion tube than relating inflammability to the combustion factor α because α involves the burning rates after ignition has occurred and these rates are difficult to determine at present. Also, the effects of any ignition lag the mixture may possess is included in the measurement of flame-front position.

The data obtained with the combustion tube (fig. 8) are in agreement with the results on inflammability given in the literature. Figure 8 shows qualitatively the effect of fuel-air ratio and velocity on flame-front position. In agreement with the theoretical reasoning which suggested equation (6), it is also found that an increase of electrical power moves the flame front farther upstream.

SUMMARY OF RESULTS

From a study of the combustion of flowing gas in a combustion tube, the following results were obtained:

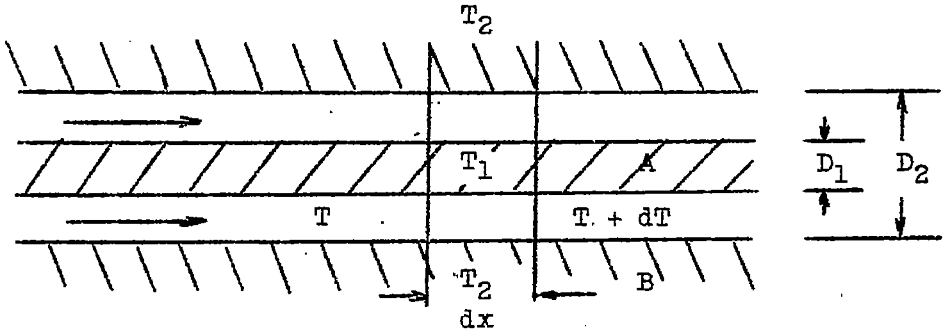
1. The greater the surface-volume ratio, or the greater the amount of heat addible to the gas stream, the greater the inlet-mixture velocity at which appreciable combustion can be obtained.

2. For a given fuel-air ratio, the total rate of heat output (Btu/sec), equal to the sum of the electrical and chemical energy released, increases with increasing velocity. However, both the extent of combustion, as measured by the combustion factor α, and the total heat output (Btu/lb of fuel) decrease with increase of velocity for most of the fuel-air ratios tested.

3. The most inflammable mixtures, as determined by the length of heating element necessary to produce ignition, are those of approximately stoichiometric proportions of fuel and air.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, April 1, 1946.

APPENDIX - HEAT TRANSFER TO A FLUID FLOWING IN AN ANNULUS



If A is a cylindrical heating element whose surface temperature is T_1 and B is a concentric outer wall at temperature T_2, the heat absorbed per unit time dq in a section dx by fluid flowing with a mass velocity G is

$$dq = \frac{\pi c_p G}{4} (D_2^2 - D_1^2)\ dT \tag{7}$$

where c_p is the mean specific heat at constant pressure in Btu/(lb)(°F).

The heat absorbed by the gas is equal to the heat transferred from the walls in length dx.

$$dq = \pi D_2 h_2 dx\ (T_2 - T) + \pi D_1 h_1 dx\ (T_1 - T) \tag{8}$$

where h_1 and h_2 are heat-transfer coefficients in Btu/(sec)(ft^2)(°F). If the heat-transfer coefficients h_1 and h_2 are assumed to be equal, equation (8) becomes

$$dq = \pi h dx\ [D_2 T_2 + D_1 T_1 - T(D_2 - D_1)] \tag{9}$$

Equate (7) and (9) and define

$$a = \frac{D_1}{D_1 + D_2},\ b = \frac{D_2}{D_1 + D_2},\ \text{and}\ \ D_e = D_2 - D_1$$

which gives

$$dx = \frac{c_p \, GD_e}{4h}\left(\frac{dT}{aT_1 + bT_2 - T}\right) \tag{10}$$

Since G is constant and if c_p, h, a, and b are also assumed constant, equation (10) can be integrated between the limits $x = 0$, L and $T = T_i$, T_o giving

$$L = \frac{c_p \, GD_e}{4h} \log_e \left(\frac{aT_1 + bT_2 - T_i}{aT_1 + bT_2 - T_o}\right)$$

where

L length of combustion annulus, ft

T_i, T_o inlet and outlet fluid temperatures, respectively, °F

which may be shown to be equivalent to

$$T_o - T_i = \left[aT_1 + bT_2 - T_i\right]\left[1 - \exp\left(\frac{-4hL}{c_p \, GD_e}\right)\right] \tag{11}$$

For h there may be substituted (reference 2, p. 202) a relation of the form

$$h = C_o\left(\frac{D_2}{D_1}\right)^u \left(\frac{D_e G}{\mu}\right)^v \left(\frac{c_p \, \mu}{k}\right)^z \frac{k}{D_e}$$

and also $\rho V = G$, $T_{av} = aT_1 + bT_2$

where

C_o dimensionless constant

μ fluid viscosity, lb mass/(sec)(ft)

k thermal conductivity, Btu/(sec)(ft^2)(°F/ft)

ρ fluid density, lb mass/cu ft

V fluid velocity, ft/sec

T_{av} weighted average temperature of inside surfaces, °F

Then, if ρ, c_p, μ, and k are assumed constant,

$$T_o - T_i = (T_{av} - T_i)\left[1 - \exp\left(\frac{-C_1 L}{D_e^{2-v}\, V^{1-v}}\right)\right] \tag{12}$$

where $v \approx 0.8$. Equation (12), presented as equation (6) in the text, gives T_{ig} for T_o for the case where the outlet temperature T_o corresponds to the ignition temperature of the fluid.

The assumption that $h_1 = h_2$ is questionable since recent data (references 6 and 7) show that the values for the inner and outer wall coefficients are different. Equation (12) is based on inlet conditions and thus neglects the variation of ρ, V, and h with temperature. Also, T_{av} in equation (12) is a complex weighted average temperature in the case where T_1 and T_2 are not constant along the length of the annulus.

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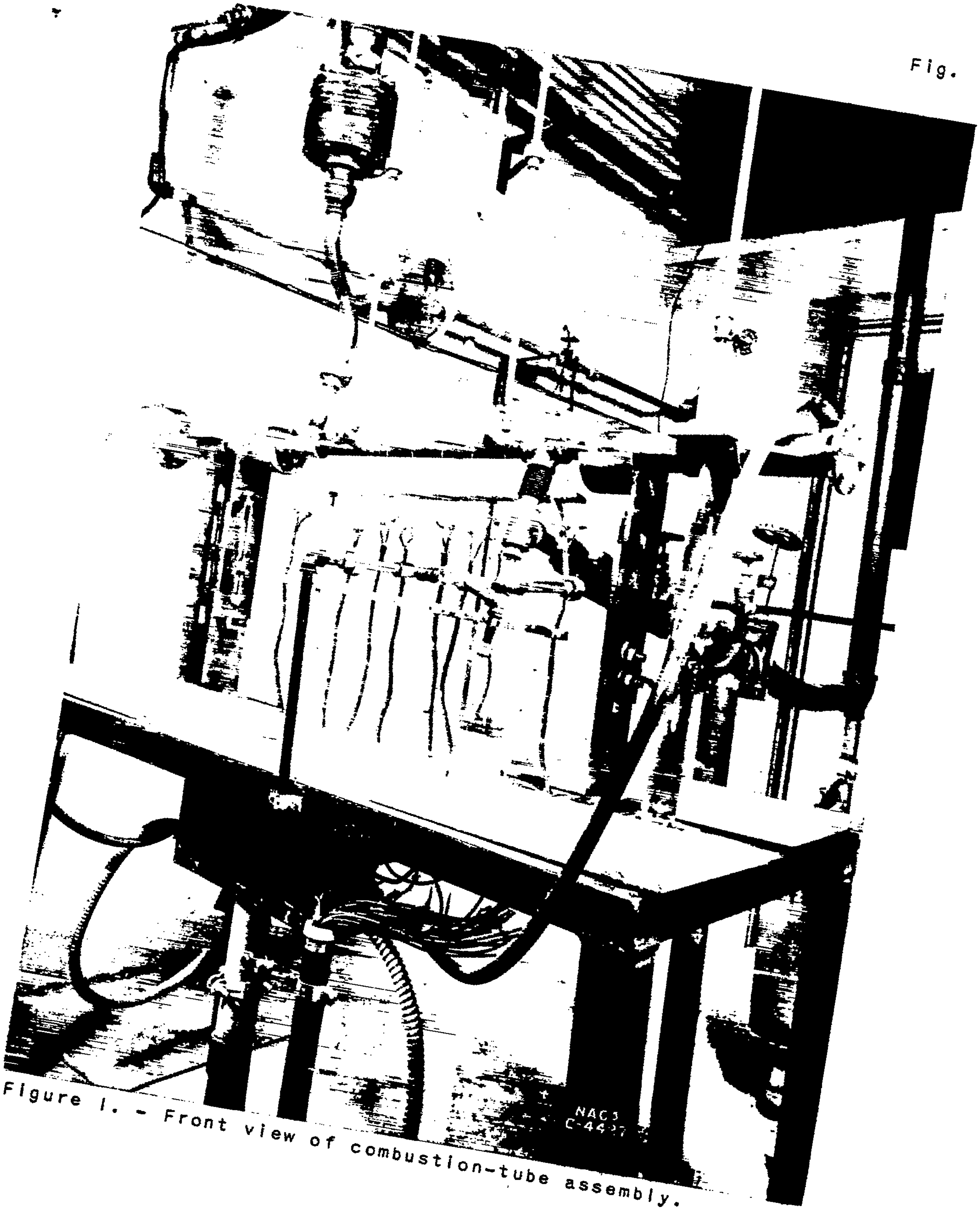
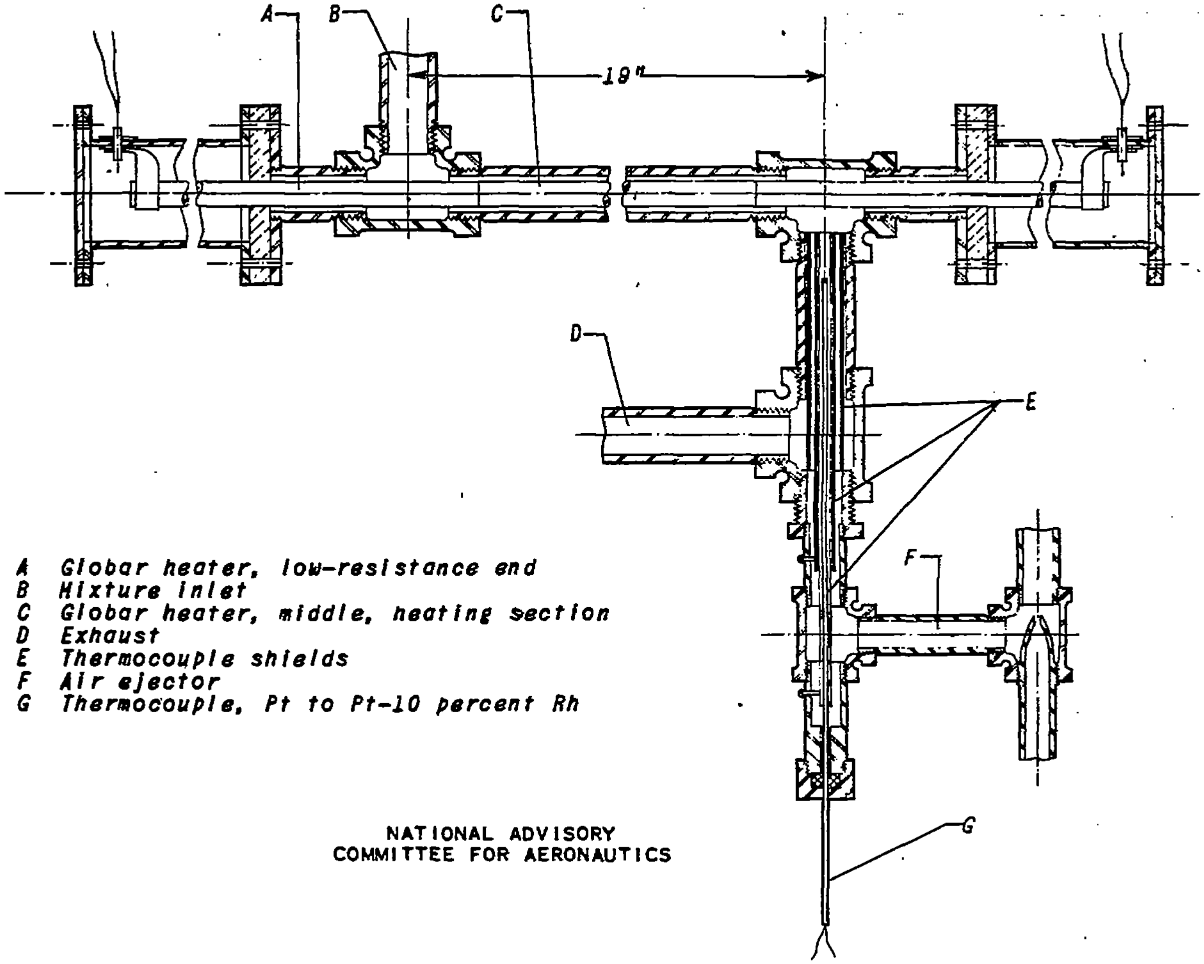


Figure 1. - Front view of combustion-tube assembly.



A Globar heater, low-resistance end
B Mixture inlet
C Globar heater, middle, heating section
D Exhaust
E Thermocouple shields
F Air ejector
G Thermocouple, Pt to Pt-10 percent Rh

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Figure 2. - Sectional view of combustion tube and exhaust thermocouple.

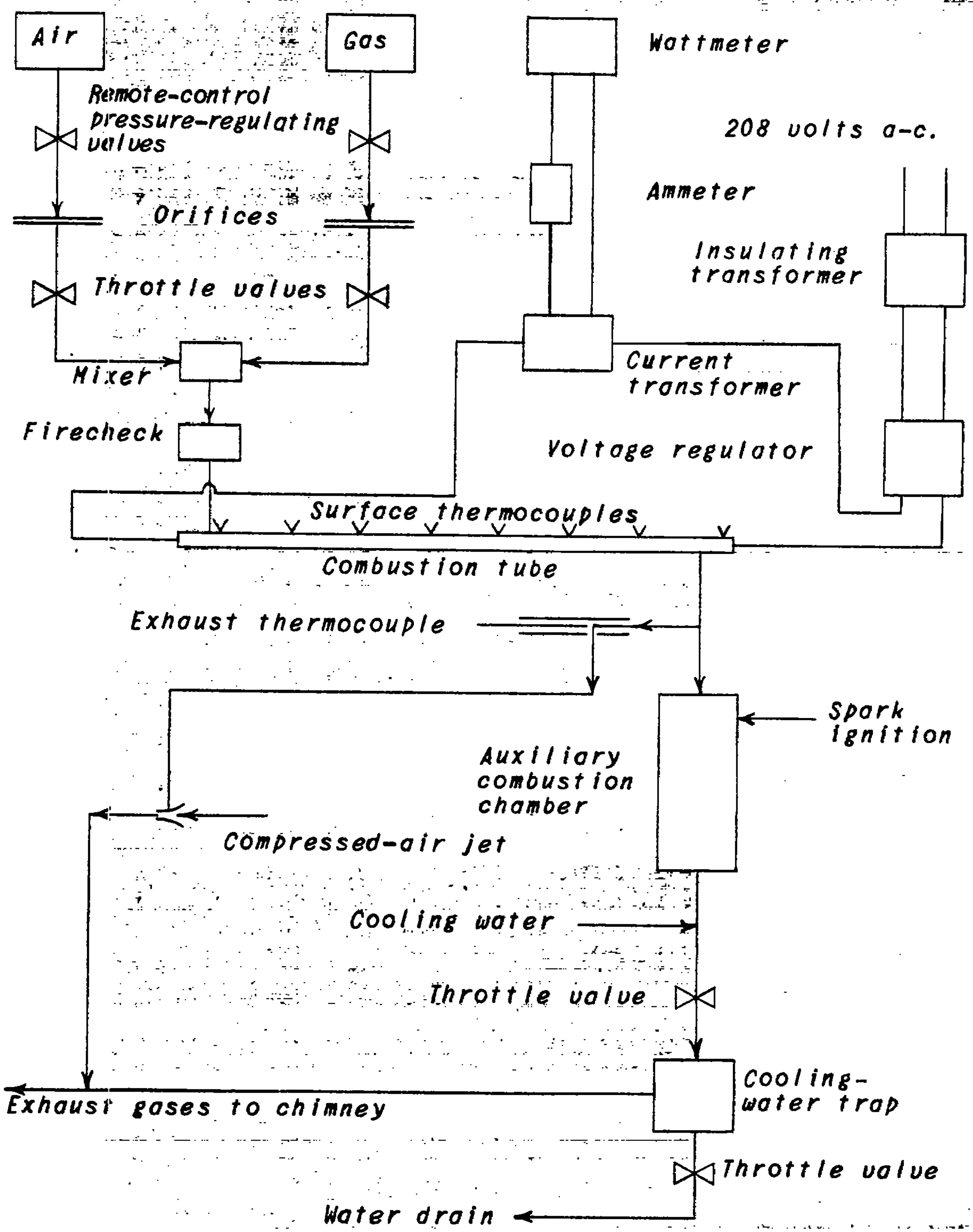

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Figure 3. - Flow diagram for combustion-tube apparatus.

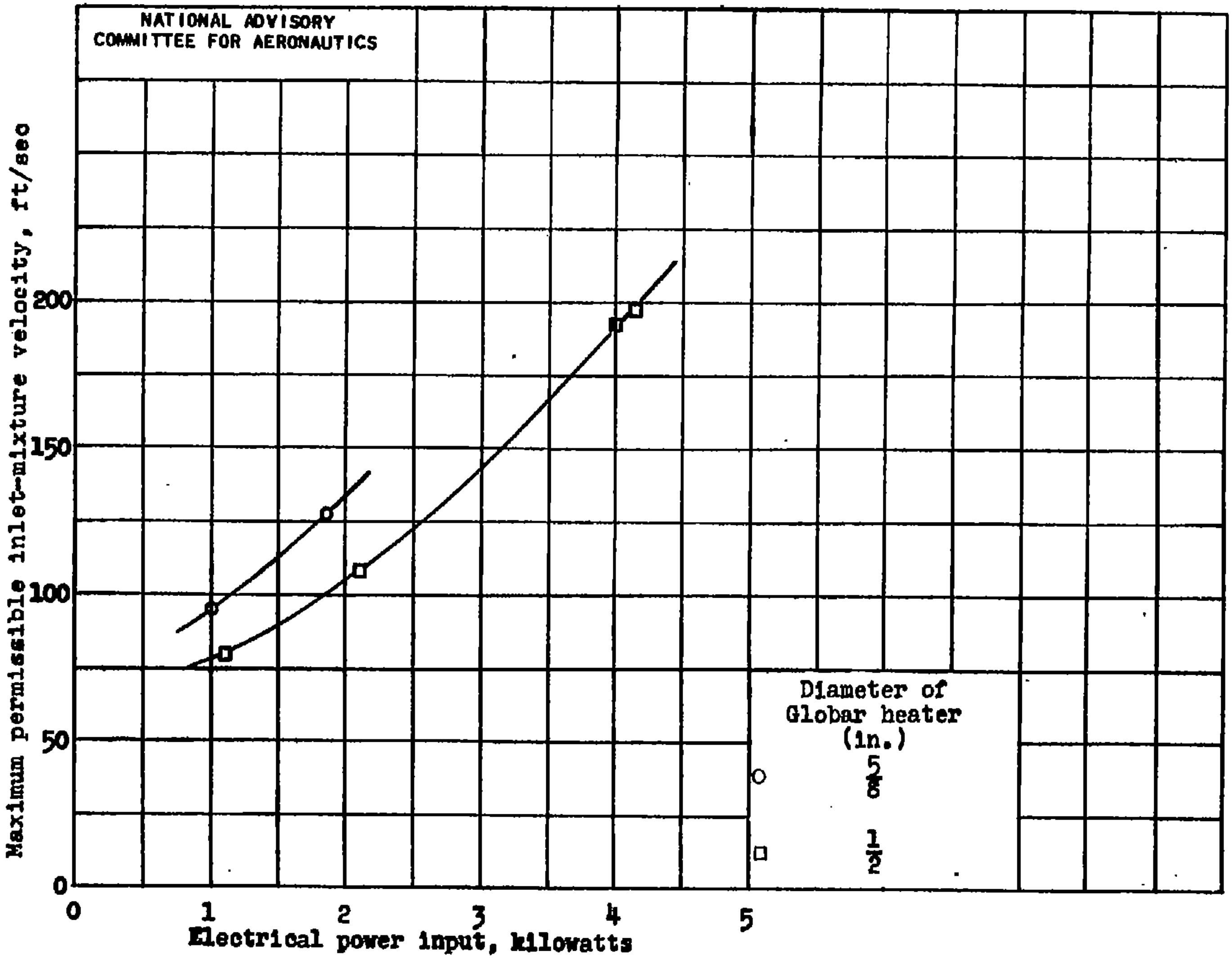


Figure 4. - Effect of heat addition on maximum permissible inlet-mixture velocity at which ignition is obtained. Gas pressure, 1 to $1\frac{1}{2}$ atmospheres; inlet temperature, 80° F; overall length of combustion tube, 19 inches; inside diameter of outer tube, 0.742 inch.

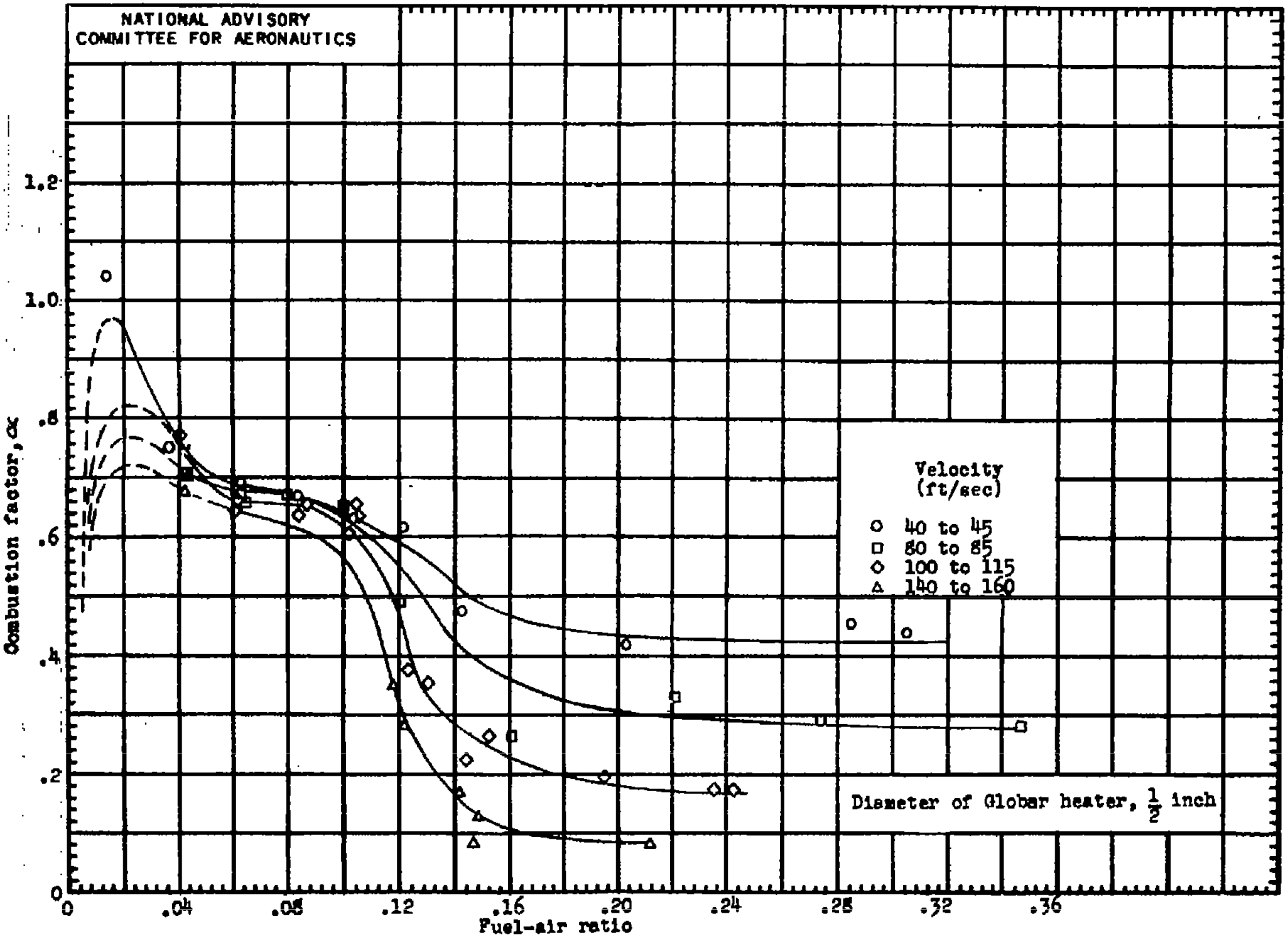


Figure 5. - Effect of fuel-air ratio and inlet-mixture velocity on combustion factor. Electrical power input, 3.6 to 4.2 kilowatts (3.4 to 4.0 Btu/sec); gas pressure, 1 to $1\frac{1}{2}$ atmospheres; inlet temperature, 80° F; over-all length of combustion tube, 19 inches; inside diameter of outer tube, 0.742 inch.

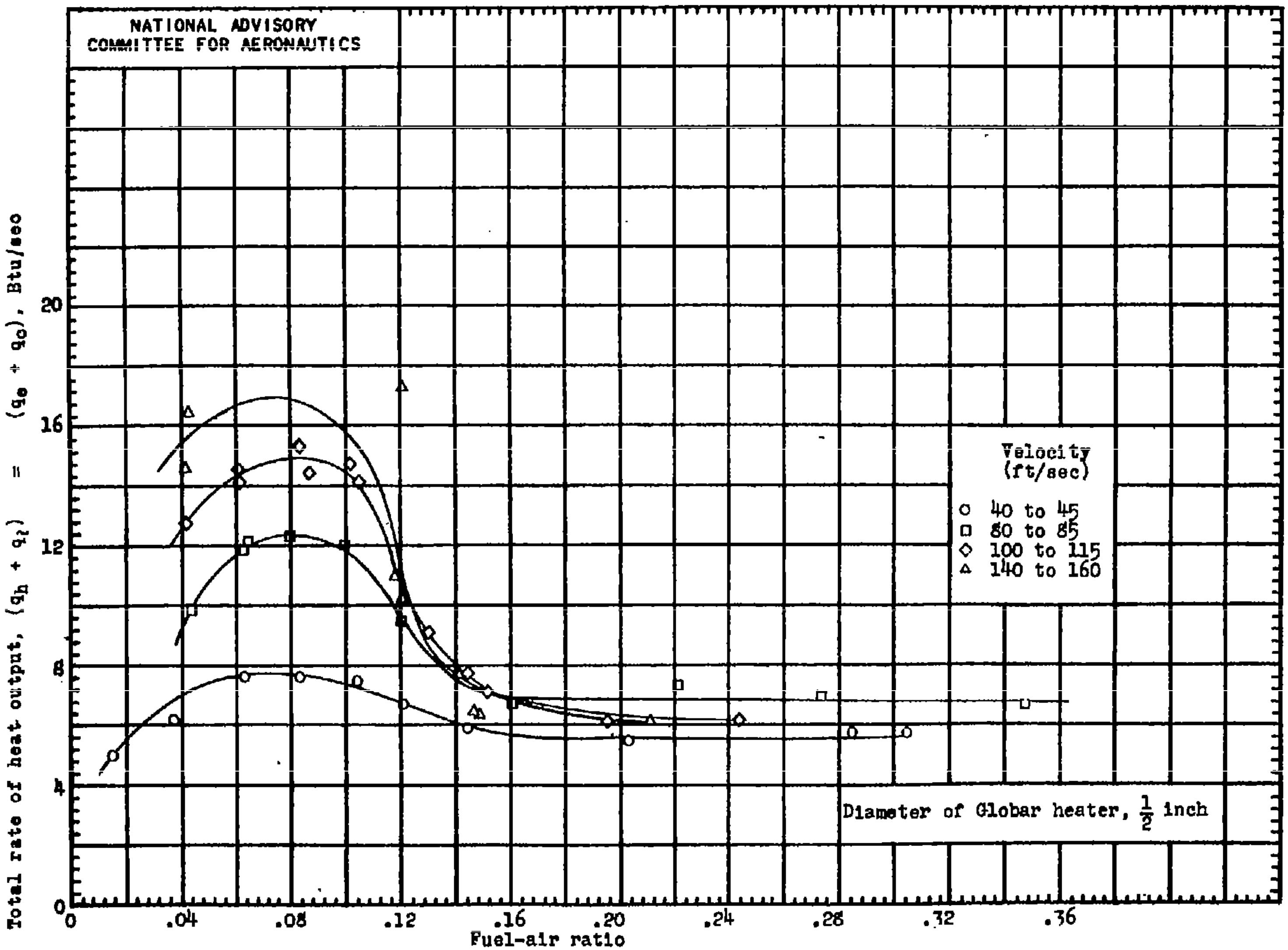


Figure 6. - Effect of fuel-air ratio and inlet-mixture velocity on total rate of heat output. Electrical power input, 3.6 to 4.2 kilowatts (3.4 to 4.0 Btu/sec); gas pressure, 1 to $1\frac{1}{2}$ atmospheres; inlet temperature, 80° F; over-all length of combustion tube, 19 inches; inside diameter of outer tube, 0.742 inch.

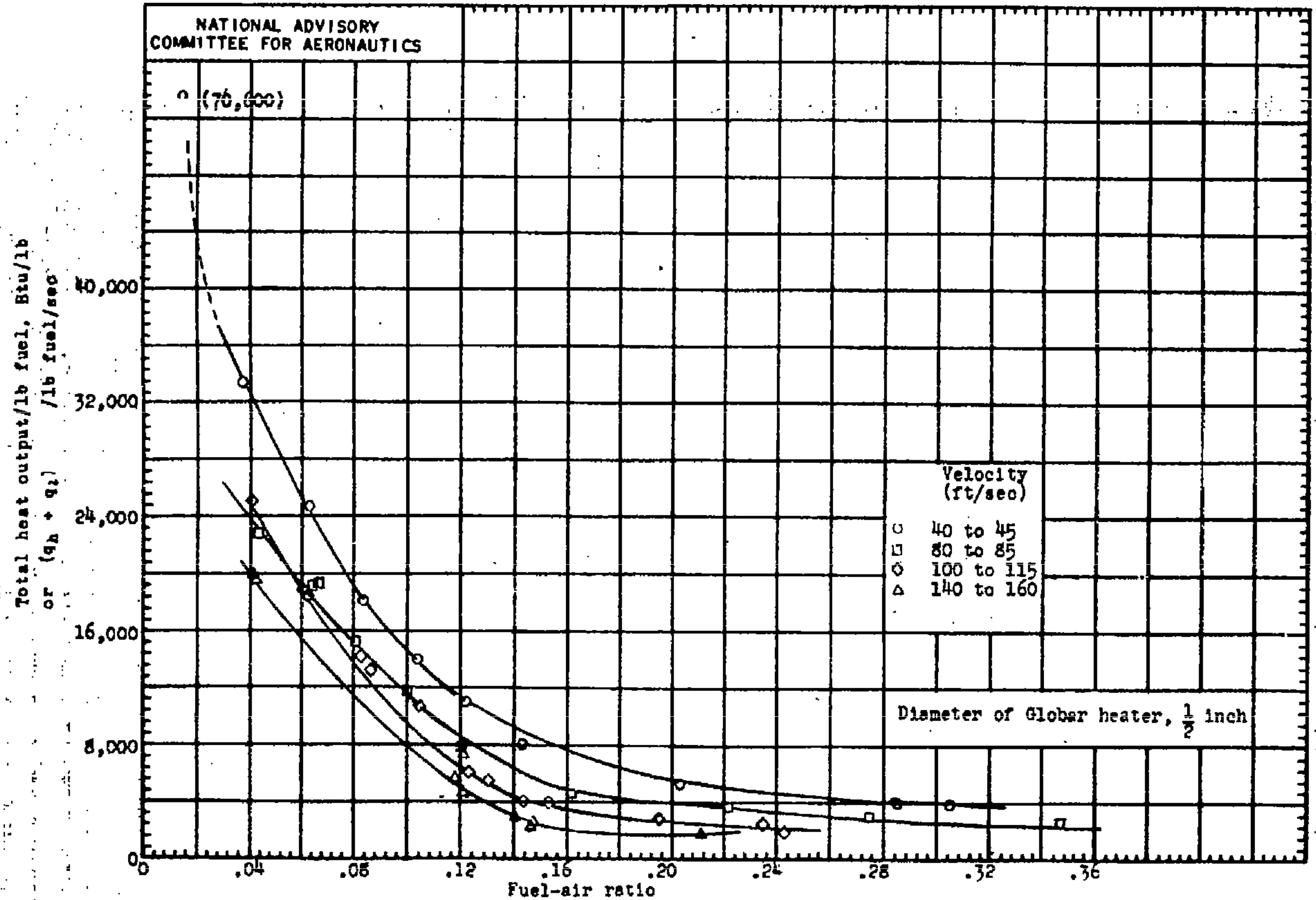
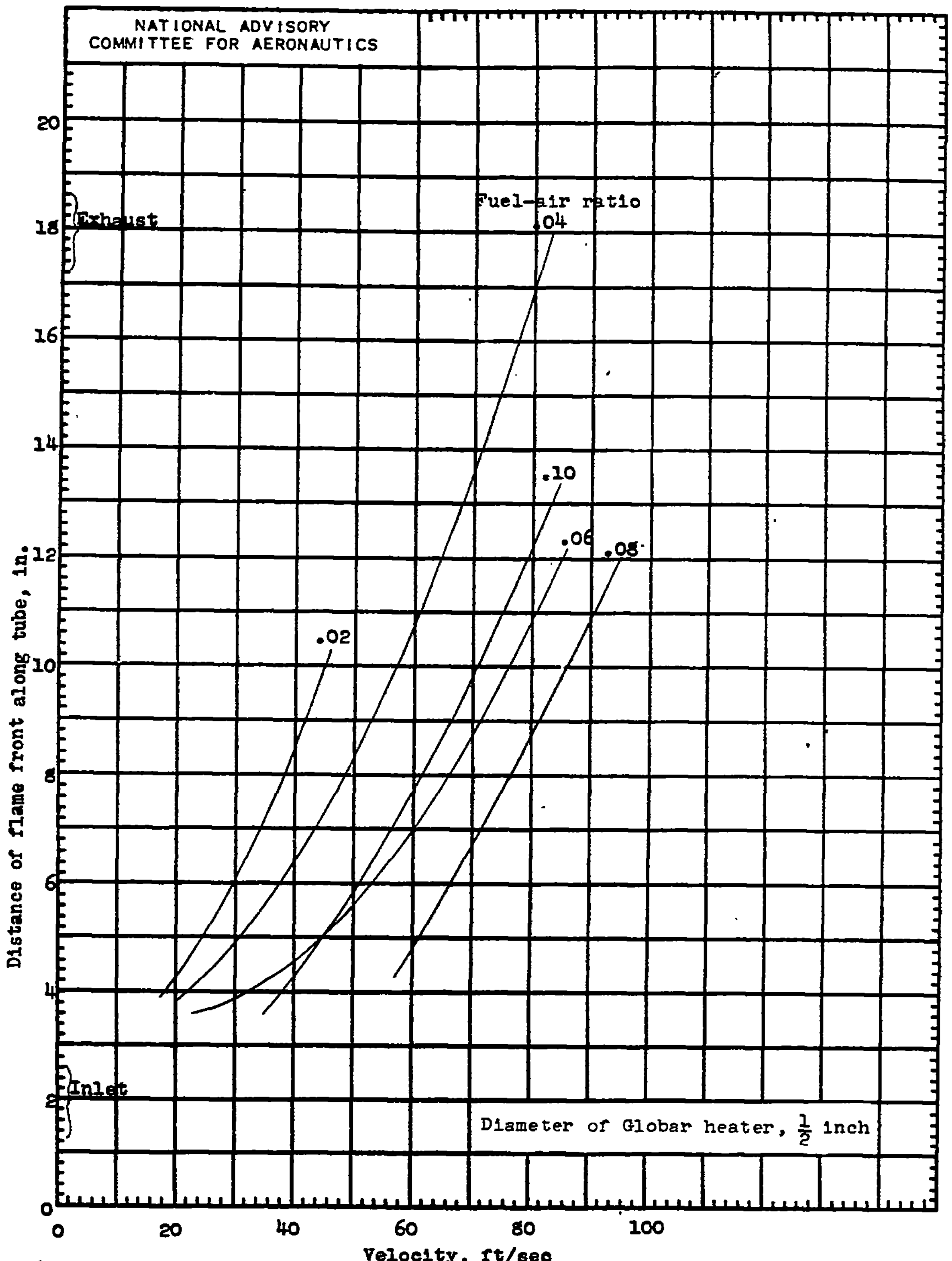
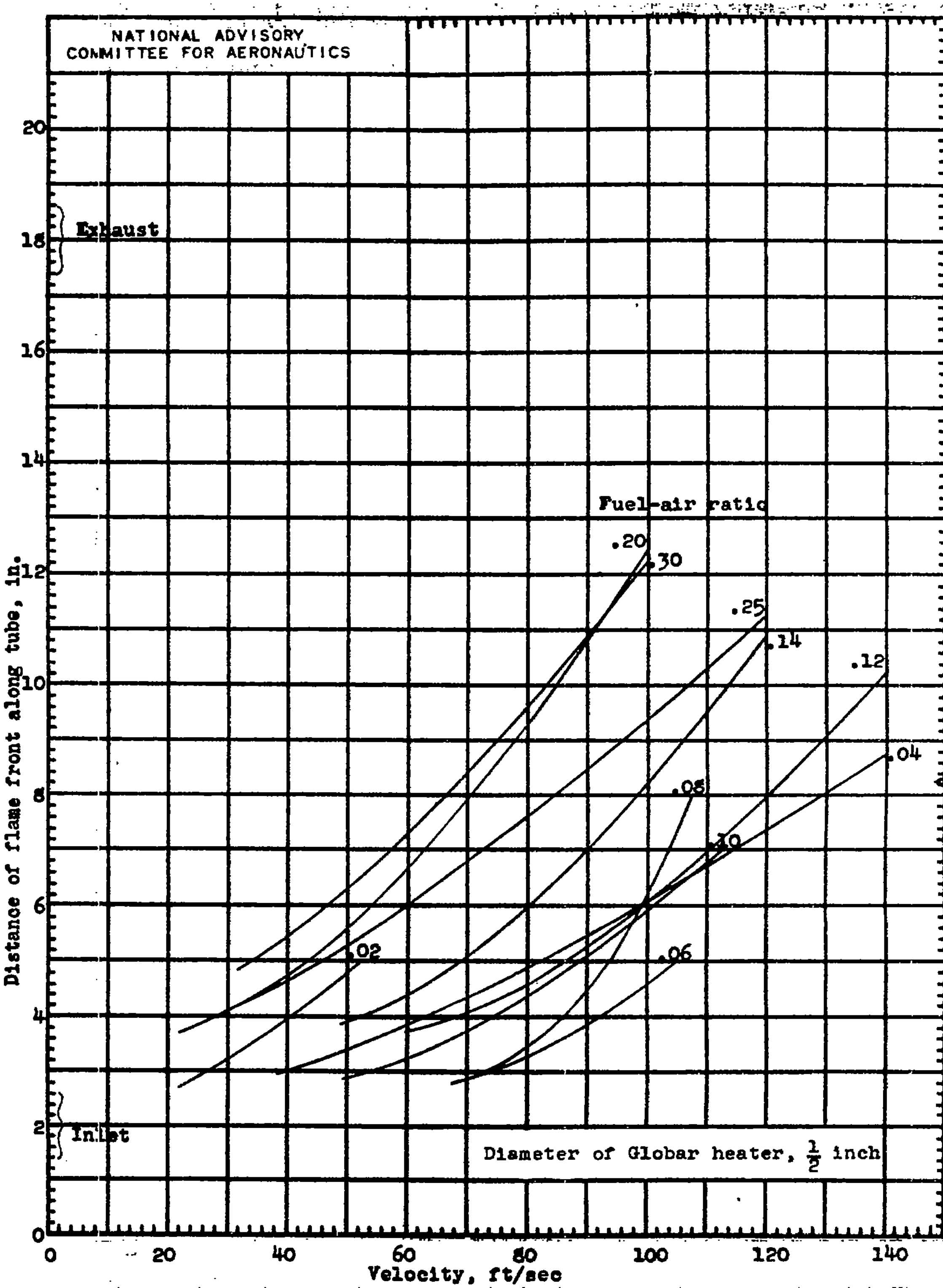


Figure 7. - Effect of fuel-air ratio and inlet-mixture velocity on total heat output per pound of fuel Electrical power input, 3.6 to 4.2 kilowatts (3.4 to 4.0 Btu/sec); gas pressure, 1 to $1\frac{1}{2}$ atmospheres; inlet-air temperature, 80° F; over-all length of combustion tube, 19 inches; inside diameter of outer tube, 0.742 inch.



(a) Power input, 2 kilowatts.

Figure 8. - Effect of fuel-air ratio and inlet-mixture velocity on position of flame front. Gas pressure, 1 to $1\frac{1}{2}$ atmospheres; inlet temperature, 80° F; over-all length of combustion tube, 19 inches; inside diamter of outer tube, 0.742 inch.



(b) Power input, 4 kilowatts.
Figure 8. - Concluded.